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Splitting the dynamic exergy destruction within a building energy system into endogenous and exogenous parts using measured data from the building automation system

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Summary

This study presents a novel approach to apply advanced exergy analysis to a dynamic system. The main building of the E.ON Energy Research Center located in Aachen, Germany, which is a large, complex and multifunctional building is considered as the case study. Results of the present study show a substantial interdependency among different components of the considered building, meaning that a significant improvement in the overall performance of the building could be achieved through the implementation of a better control algorithm. Furthermore, it is shown that the improvement suggestions and optimization priorities obtained from an advanced exergy analysis are more rational and reasonable compared with a conventional exergy analysis. For instance, based on the results of this study, the Façade ventilation units and the active chilled beams in the cooling network of the considered building cause a large amount of exergy destruction in other components of the system. So, based on an advanced exergy analysis these components have the highest priority for optimization. Improvement of these components not only decreases the endogenous exergy destruction within them but also results in lower (exogenous) exergy destructions in the remaining components of the system. In a conventional exergy analysis, however, only exergy destructions within system components are calculated and the influence of components on each other cannot be obtained.

KEYWORDS

building energy systems, dynamic exergy destruction, endogenous, exogenous, measured data, mexogenous

Abbreviations: ACB, Active Chilled Beam; AHU, Air Handling Unit; BAS, Building Automation System; BES, Building Energy System; CCA, Concrete Core Activation; CHP, Combined Heat and Power; ERC, Energy Research Center; FVU, Façade Ventilation Unit; SQL, Structured Query Language; UFH, Underfloor Heating.

1 | INTRODUCTION

The first law of thermodynamics is an essential tool for modeling and analyzing technical systems. According to this law, the total amount of energy is always conserved in an energy conversion process, only its form might change. This kind of analysis, however, does not always provide information on the real inefficiencies in a system and on the improvement potentials. The second law of thermodynamics overcomes these limitations by considering the irreversibilities in energy conversion processes in terms of entropy generation that is always positive and decreases the useful work that can be obtained by a process.

Exergy analysis merges the first and the second laws of thermodynamics and enhances the analysis by calculating both the quantity and the quality of energy. Exergy is a thermodynamic property of a system that characterizes the degree of the departure of the state of a system from the state of the environment. It shows the full potential of an energy carrier to generate useful work when it is brought into complete (thermo-mechanical and chemical) equilibrium with the environment.

A conventional exergy analysis aims to identify the location, magnitude and causes of thermodynamic inefficiencies known as exergy destruction. When an exergy analysis is carried out based on the definition of the fuel and product exergies,[1] in addition to the exergy destruction, the exergetic efficiency can also be calculated for each component of a system. This parameter is a good measure to compare the performance of similar components from the thermodynamic point of view. Reference 2 provides detailed information together with good examples of applications of exergy analysis.

The advanced exergy analysis was introduced by splitting the exergy destruction into unavoidable and avoidable parts[3,4] and later into endogenous and exogenous parts.[5-7] The unavoidable exergy destruction corresponds to the minimum exergy destruction in each component imposed by physical, technological, and economic limitations. The difference between the total and the unavoidable exergy destruction represents the avoidable exergy destruction that unveils the real potential for improving a component thermodynamically. The endogenous exergy destruction within a component corresponds only to intrinsic irreversibilities within the same component. The assumption used to calculate endogenous exergy destruction is that only the component under consideration is in the "real" operation (i.e., with exergy destruction) and the rest of the system is thermodynamically "ideal" (i.e., without exergy destruction). In this situation, the total exergy destruction within the overall system is equal to the (endogenous) exergy destruction within the component being analyzed, because in other components of the system exergy destruction is equal to zero. The exogenous part of the exergy destruction in a component is primarily caused by the irreversibilities within the remaining components. This means that thermodynamic inefficiencies in each component of a system cause not only endogenous exergy destruction in the same component, but also exogenous exergy destruction in the rest of the system.

Advanced exergy analysis is a strong tool that complements the results of a conventional exergy analysis and improves our understanding of the thermodynamic inefficiencies and the interdependencies among system components. The application of advanced exergy analysis to different types of systems and its advantages over a conventional exergy analysis are demonstrated in several studies. For instance, a conventional exergy analysis of a milk powder production factory[8] shows that the gas burner and the spray dryer are the most important components in this system. However, based on the results of an advanced exergy analysis, evaporators have the highest potential for improvement, because of the large amount of avoidable exergy destruction in these components. In another study, conventional and advanced exergy analysis are both applied to a geothermal driven dual fluid organic Rankine cycle[9] and it is shown that the optimization suggestions provided by an advanced exergy analysis are different from a conventional exergy analysis and are more rational. According to the results of an exergy analysis applied to a solar flat plate collector[10] exergy destruction in the absorber plate-sun is the largest one in the system. However, the advanced exergy analysis reveals that most of the exergy destruction in this component is unavoidable, whereas in the glass cover a large amount of exergy destruction can be avoided.

All studies about the application of advanced exergy analysis including the abovementioned ones are based on the steady-state operation of the systems, mainly at the nominal (i.e., full-load) operation. The primary goal, in this case, is the "design optimization" (e.g., finding optimal design parameters or system structure). However, most of the energy systems do not always remain at the full-load conditions; they might undergo part-load operations depending on the requested demand that they must fulfill. An optimized system based on the full-load operation is not optimal anymore, when the system is in part-load operation. In this regard, the objective of an advanced exergy analysis is to optimize the "operation" of the system and to improve the control system.

The operation of building energy systems (BESs) is highly non-steady-state because of diurnal and seasonal disturbances coupled with complex patterns of user demands and requirements. Therefore, BES is an appropriate case study to demonstrate the proposed methodology for applying dynamic advanced exergy analysis. Our case study deals with a large complex building that includes a variety of energy conversion, distribution, storage and supply technologies. The considered building has an extensive data collection and monitoring system that provides us the opportunity to apply advanced exergy analysis to a *real* system. The input data for this study are the measured data from temperature, pressure and volume flow rate sensors in different parts of the building. One main advantage of the proposed methodology is that no commercial simulation platform is required to perform the advanced exergy analysis. In the present article, the outdoor temperature, which changes with time, is chosen as the reference temperature for the exergy analysis. Here, only the interactions among system components are studied by splitting the exergy destruction into endogenous and exogenous parts. Unavoidable and avoidable exergy destructions are beyond the scope of this study and will be investigated in our future work.

2 | CASE STUDY

2.1 | The building

The main building of the E.ON Energy Research Center (E.ON ERC), located in the Campus Melaten of RWTH Aachen University in Germany, is considered as the case study. The building with a net floor area of 7222 m^2 is a large commercial building hosting more than 200 people. A comprehensive dynamic exergetic assessment of this building was carried out in our previous study[11] and exergy destructions within all components and sub-systems were obtained. The present study enhances the results of the previous one by splitting the exergy destructions in all components of the system into endogenous and exogenous parts. Thus, this study takes a step forward in the application of exergy-based methods in buildings energy systems.

Since the considered building offers different services to different types of end-users, it is called a multifunctional building. High-temperature heating and low-temperature cooling networks are installed in laboratories for research activities and experimental work. Moreover, the heating and cooling demands of the building are covered through low-temperature heating and high-temperature cooling networks using a variety of energy supply technologies such as Façade Ventilation Unit (FVU), Active Chilled Beam (ACB), Concrete Core Activation (CCA), Underfloor Heating (UFH), etc. For more information about the energy concept of the building see References 11 and 12.

2.2 | Data collection and processing

This study conducts a dynamic advanced exergy analysis using measured data such as temperatures, pressures, volume flow rates, operating loads of different energy conversion facilities, etc. The data were first recorded every minute by different types of sensors in more than 150 measuring points throughout the building and then were stored in the SQL (Structured Query Language) database.[13,14] Several scripts were developed in MATLAB to access the stored data from the SQL database, and to conduct a plausibility check using the mass and energy balances. Finally, the adjusted set of data is used to perform a dynamic advanced exergy analysis. The main advantage of the proposed approach is that it does not require any commercial software for calculations and can directly be implemented in the building automation system (BAS).

3 | METHODOLOGY

3.1 | Exergy calculated from the measured data

The exergy of a system is a combined property of the system and its thermodynamic (reference) environment. Therefore, it can be calculated only when the state of the system and the state of the reference environment are both known. In this study, the state of the system is defined using measured temperatures and pressures in different parts of the BES. Furthermore, since the outdoor air is chosen as the reference environment here, weather data recorded on-site are used to specify the state of the reference environment.

The selection of the outdoor air as the reference state poses some challenges in an exergy analysis because the ambient temperature changes with time, and can sometimes be above or below the operating temperatures in the system, or it can even cross these temperatures. In such situations, additional effort is required to split the physical exergy into its thermal and mechanical parts and to define fuel and product exergies accordingly. Reference 11 categorizes the operating conditions of the heating and cooling devices in buildings according to different reference temperatures and provides the proper definition of the fuel and the product using thermal and mechanical exergies separately.

Exergy is defined as the maximum theoretical useful work that can be obtained when the system being considered is brought into complete (physical and chemical) equilibrium with the reference state.[15] In our case study, the chemical part of exergy only appears in the boilers and in the combined heat and power (CHP), where the energy of the natural gas is converted from the chemical to the thermal and electrical forms. For the sake of simplicity, the chemical exergy of the natural gas was estimated based on its higher heating value.[16] For the rest of the system, since the working fluids are mostly air and liquid water, the formulation of the physical exergy is simplified and is calculated at each time step using Equation (1):

$$\dot{E}_j^{\mathrm{PH}}(t)=\begin{cases}\dot{m}_j(t)\cdot\left[\underbrace{c_{\mathrm{p_w}}\cdot\left(\left(T_j(t)-T_0(t)\right)-T_0(t)\ln\frac{T_j(t)}{T_0(t)}\right)}_{e_j^{\mathrm{T}}(t)}+\underbrace{\frac{p_j(t)-p_0(t)}{\rho_{\mathrm{w}}}}_{e_j^{\mathrm{M}}(t)}\right] & \text{liquid water}\\ \dot{m}_j(t)\cdot\left[\underbrace{c_{\mathrm{p_a}}\cdot\left(\left(T_j(t)-T_0(t)\right)-T_0(t)\ln\frac{T_j(t)}{T_0(t)}\right)}_{e_j^{\mathrm{T}}(t)}+\underbrace{T_0(t)\cdot R\cdot\ln\frac{p_j(t)}{p_0(t)}}_{e_j^{\mathrm{M}}(t)}\right] & \text{air}\end{cases} \tag{1}$$

Here, $T_0(t)$ and $p_0(t)$ represent the ambient temperature and pressure at each time step. They are recorded by the sensors installed in the weather station on the roof of the building. $\dot{m}_j(t)$, $T_j(t)$, and $p_j(t)$ are the mass flow rate, the temperature, and the pressure (of water or air), respectively. These parameters are also obtained from the BAS and their values are updated every one minute.

3.2 | Exergy destruction

The exergy destruction rate within the component k is a measure of the thermodynamic inefficiencies within this component. It is calculated as the difference between the incoming and outgoing exergies in the forms of heat, work, and material as well as the change of the exergy stored in the component. A graphical representation of the dynamic exergy balance for the kth component is illustrated in Figure 1 and the corresponding exergy destruction within this component is calculated from Equation (2):

$$\dot{E}_{\mathrm{D}}=\underbrace{\sum_m \dot{Q}_m\cdot\left(1-\frac{T_0}{T_m}\right)}_{\sum \dot{E}_{\dot{Q}_{\mathrm{in}}}-\sum \dot{E}_{\dot{Q}_{\mathrm{out}}}}+\underbrace{\sum_n \dot{W}_n}_{\sum \dot{W}_{\mathrm{in}}-\sum \dot{W}_{\mathrm{out}}}+\sum_i \dot{E}_{i,\mathrm{in}}-\sum_j \dot{E}_{j,\mathrm{out}}-\frac{dE_k}{dt}. \tag{2}$$

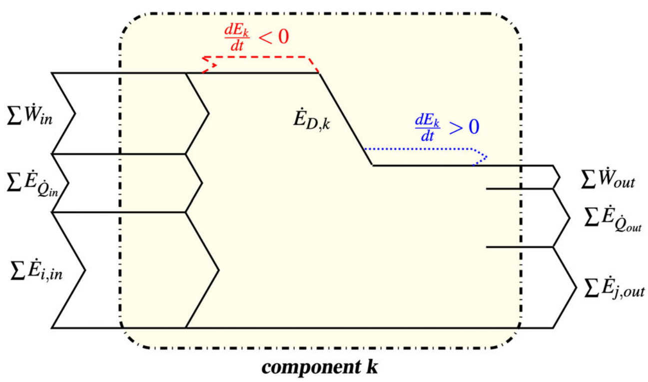

FIGURE 1 A graphical representation of the dynamic exergy balance for the component k [Colour figure can be viewed at wileyonlinelibrary.com]

This equation is based on the following sign conventions:

- heat transfer into a system is positive and heat transfer from a system is negative;
- work done by a system is negative and work done on a system is positive.

As seen in Figure 1, when the temporal exergy change of the component is positive ($dE_k/dt>0$), some part of the inlet exergy is stored in the component. In dynamic applications, it is essential to differentiate this part from the exergy destruction because the stored exergy in the components will later be used as a part of the "driving force" for generating the required product. In this case, the exergy destruction obtained from the dynamic exergy balance is smaller than just the difference between the inlet and outlet exergies. The reduction in the exergy destruction is shown with the dotted line in Figure 1.

On the contrary, when $dE_k/dt<0$, the exergetic driving force (or part of it) is provided by the exergy that had been stored in the component. Hence the exergy destruction obtained from the dynamic exergy balance would be larger than the difference between the inlet and outlet exergies. This is also shown with a dashed line in Figure 1.

According to the cases mentioned above, the term dE_k/dt must be included in the definition of fuel and product exergies in dynamic applications. This term belongs to the fuel exergy when it decreases and to the product exergy when it increases. Since the exergetic efficiency is sensitive to the definition of the fuel and product exergies, neglecting dE_k/dt would affect the results of an advanced exergy analysis.

3.3 | The method of serial arrangement for splitting exergy destruction

There are several approaches for splitting the exergy destruction into endogenous and exogenous parts. According to Reference 17, one of the most robust methods is the one based on "thermodynamic cycles"[6,18] because of well-established thermodynamic assumptions and uniform rules needed to apply this method. However, this approach requires a large number of *non-standard* simulations to predict the ideal operation of the system based on the second law of thermodynamics. The implementation of theoretical assumptions associated with the idealization of processes is not always an easy task for available commercial software.

Another method is called the "decomposition approach,"[19] and it outperforms the previous approach by reducing the calculation time significantly and by offering a more straightforward procedure for splitting the exergy destruction. However, this method does not seem to be a proper choice for our application. The reason is that for the idealization of the plant components, many mass and energy balances are required, which would be too time-consuming for the BAS. A much faster methodology to implement an advanced exergy analysis in the BAS would be more practical, even if accuracy has to be sacrificed to some extent.

In this study, a new method called "the method of serial arrangement" is used which is similar to the "engineering approach,"[5,20] but it is not graphical. This method is solely exergy-based and is founded on the formulation of the exergy balance. In order to apply this approach, first a block diagram needs to be created based on the exergy balance, in which the blocks must be connected in series. It means that the product exergy of one upstream block would be the fuel exergy to its adjacent downstream block. According to this approach, it is assumed that the exergetic efficiency of the component k remains unchanged, as the exergy destruction caused by other components of the system (i.e., the exogenous exergy destruction in component k) decreases. This method is fast, practical, and easy to implement in the BAS and does not require any additional simulation platform. In order to facilitate the implementation of the method of serial arrangement for splitting exergy destruction into endogenous and exogenous parts, the whole energy system of the E.ON ERC building is divided into 26 sub-systems, as illustrated in Figure 2.

Fuel and product exergies, as well as exergetic efficiencies for all sub-systems of the considered case study, are listed in Table 1. The exergetic efficiency of a component is defined as the ratio between product and fuel exergies and shows the percentage of the fuel exergy provided to the system that is found in the product exergy. An appropriately defined exergetic efficiency is the only variable that unambiguously characterizes the performance of a component from the thermodynamic point of view[11]:

$$\varepsilon_k = \frac{\dot{E}_{\mathrm{P}}}{\dot{E}_{\mathrm{F}}}. \tag{3}$$

The exergetic variables shown in Table 1 are obtained based on the operation of the system in the year 2015 using monitored data. Based on these parameters, endogenous and exogenous exergy destructions are obtained.

3.4 | Block diagram

After dividing the system into sub-systems and obtaining the exergetic variables listed in Table 1, a block diagram is prepared to facilitate the remaining steps. This diagram is depicted in Figure 3 and is generated based on the measured data in the E.ON ERC building for the year 2015.

3.4.1 | Final exergetic products of the system

Splitting the exergy destruction into endogenous and exogenous parts is founded on the assumption that either the exergy of the product or the exergy of the fuel of the overall system is kept constant. In our case study, since the end-users of the building request the product, it is assumed that the final product of the system always remains constant under both "ideal" and "real" operations of the system components. These final exergetic products are specified in Figure 3 with outgoing arrows (in blue color) from heating and cooling consumers in the form of thermal exergy and from the CHP in the form of electricity. It must be noted that the final exergetic product represents the exergy of the requested heating/

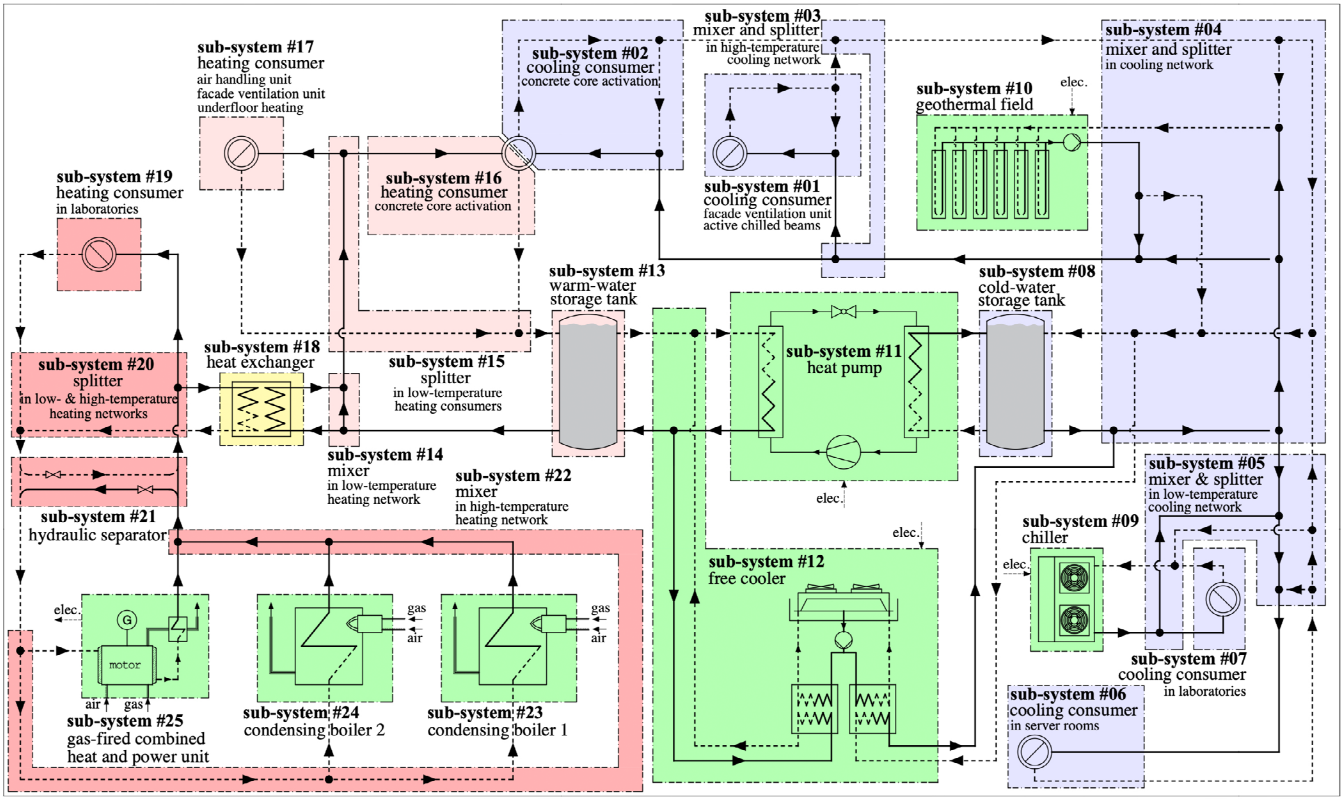

FIGURE 2 Schematic of the heating and cooling systems in the main building of the E.ON ERC (adapted from Reference 11) and boundaries of sub-systems for splitting exergy destruction [Colour figure can be viewed at wileyonlinelibrary.com]

cooling demand at the room air temperature calculated from Equation (4):

$$\dot{E}_{\mathrm{P,H/C}} = \dot{Q}_{\mathrm{H/C}} \cdot \left(1 - \frac{T_0}{T_\mathrm{z}}\right). \tag{4}$$

Here T_z is the required zone temperature which is set to 21 and 24°C for heating and cooling modes, respectively. In most of the heating and cooling consumers, in addition to the outgoing arrows, there are other incoming streams specified by dashed lines (also in blue color). These lines correspond to the cases when the exergy demand is negative, meaning that the demand could have been fulfilled directly by the reference environment (i.e., outdoor air) without operation of any heating or cooling devices. This interpretation can be justified by Equation (4), too. For instance, in the cooling mode, $\dot{Q}_{\mathrm{H/C}}$ is negative, because heat must be removed from the building (see the assumption we made for Equation (2)). Therefore, if $T_0 < T_\mathrm{z}$, then $(1 - T_0/T_\mathrm{z})$ would be positive and thus the exergy demand of the zone becomes negative. In other words, when the ambient temperature is lower than the zone temperature, apparently there is no need to cool down the zone by using cooling devices. Indeed, the demand could be merely covered by the outdoor air. However, due to an inefficient control system or to the restrictions on the indoor air quality, the cooling demand in such situations could not be covered directly by the outside air.

To visualize this situation, all negative exergy demands are shown in the opposite directions with regard to the direction of the positive exergy demands. These exergies flow into the consumers and are destroyed within these components. For this reason, they are excluded from the final product of the system and are only considered to calculate the exergy destruction and the exergetic efficiency of the components in their "real" operation mode. Table 2 shows the final product exergies for our case study. These values are obtained by integrating Equation (4) over the entire year 2015 using the monitored data from the BAS.

3.4.2 | Exergy supplied to each sub-system in ideal and real operations of the plant

As seen in Figure 3, there are some solid lines and some dashed lines connecting different sub-systems of the plant. The solid lines correspond to the supplied exergies to each component of the system in both real and ideal operations of the system.

The "ideal" supplied exergies are shown inside parentheses and are obtained based on the assumption that the

TABLE 1 Exergetic results for all sub-systems of the considered building in the year 2015

	Sub-system, k	$E_{F,k}$ (MWh)	$E_{P,k}$ (MWh)	$E_{D,k}$ (MWh)	ε_k (%)
1	Cooling consumer FVU and ACB	7.756	1.596	6.161	20.57
2	Cooling consumer CCA	0.534	0.177	0.357	33.15
3	Mixer and splitter in high-temperature cooling network	2.997	2.929	0.068	97.73
4	Mixer and splitter in cooling network	5.582	5.298	0.284	94.91
5	Mixer and splitter in low-temperature cooling network	1.472	0.875	0.597	59.44
6	Cooling consumer in server rooms	2.691	0.838	1.853	31.14
7	Cooling consumer in laboratories	0.330	0.048	0.282	14.54
8	Cold-water storage tank	5.468	4.417	1.051	80.78
9	Chiller	7.214	0.211	7.003	2.92
10	Geothermal field	3.400	1.530	1.870	–
11	Heat pump	165.429	63.431	101.998	38.34
12	Free cooler	67.083	0.001	67.082	–
13	Warm-water storage tank	19.142	17.788	1.346	97.84
14	Mixer in low-temperature heating network	21.596	20.533	1.063	95.08
15	Splitter in low-temperature heating consumers	20.533	20.002	0.531	97.41
16	Heating consumer CCA	5.906	3.634	2.272	61.53
17	Heating consumer AHU, FVU and UFH	14.104	8.122	5.982	57.59
18	Heat exchanger	13.140	5.903	7.237	44.92
19	Heating consumer in laboratories	20.990	15.000	5.990	71.46
20	Splitter in low- and high-temperature heating networks	34.470	34.130	0.340	99.01
21	Hydraulic separator	35.113	34.470	0.643	98.17
22	Mixer in high-temperature heating network	35.150	35.113	0.037	99.89
23	Condensing boiler 1	66.420	14.817	51.603	22.31
24	Condensing boiler 2	86.856	19.901	66.955	22.91
25	Gas-fired combined heat and power unit	3.189	1.465	1.724	45.94

entire energy system is operating ideally, meaning that the exergetic efficiencies of all sub-systems are 100%. In such a theoretical (hypothetical) situation, the total fuel exergy supplied to the whole system would be equal to the total product exergy requested by the end-users.

The "real" supplied exergies are shown without parentheses in Figure 3 and are calculated using the measured data from the BAS and represent the real operation of the system in the year 2015. The values of supplied exergy in the real operation are always higher than in the ideal operation to compensate for the thermodynamic inefficiencies within the system components.

3.4.3 | The increase of the exergy supplied to the sub-systems

In the cooling network of the building, due to the temporal changes in the reference temperature, the thermal part of the physical exergy supplied from upstream components to the downstream ones may sometimes even increase within the cooling process. For instance, to fulfill the annual cooling demand in the sub-system 1, "cooling consumer FVU and ACB", 1.074 MWh of thermal exergy was supplied to this unit. This exergy is in the form of cooling water passing through the sub-system 3, "Mixer & Splitter High-Temperature Cooling Network". The forward temperature of the cooling water to the sub-system 1 has to be lower than its return temperature. In a typical cooling mode, the ambient temperature is normally higher than both the forward and return temperatures of water. Thus, the thermal exergy will be completely transferred from the cooling medium to the conditioned zone. However, it is also possible that the ambient temperature is between the forward and return temperatures so that the exergy content of the cooling water within the cooling process first decreases and then begins to increase immediately after the temperature of the cooling water reaches the ambient temperature. However, this "gained exergy" is not in favor of the cooling

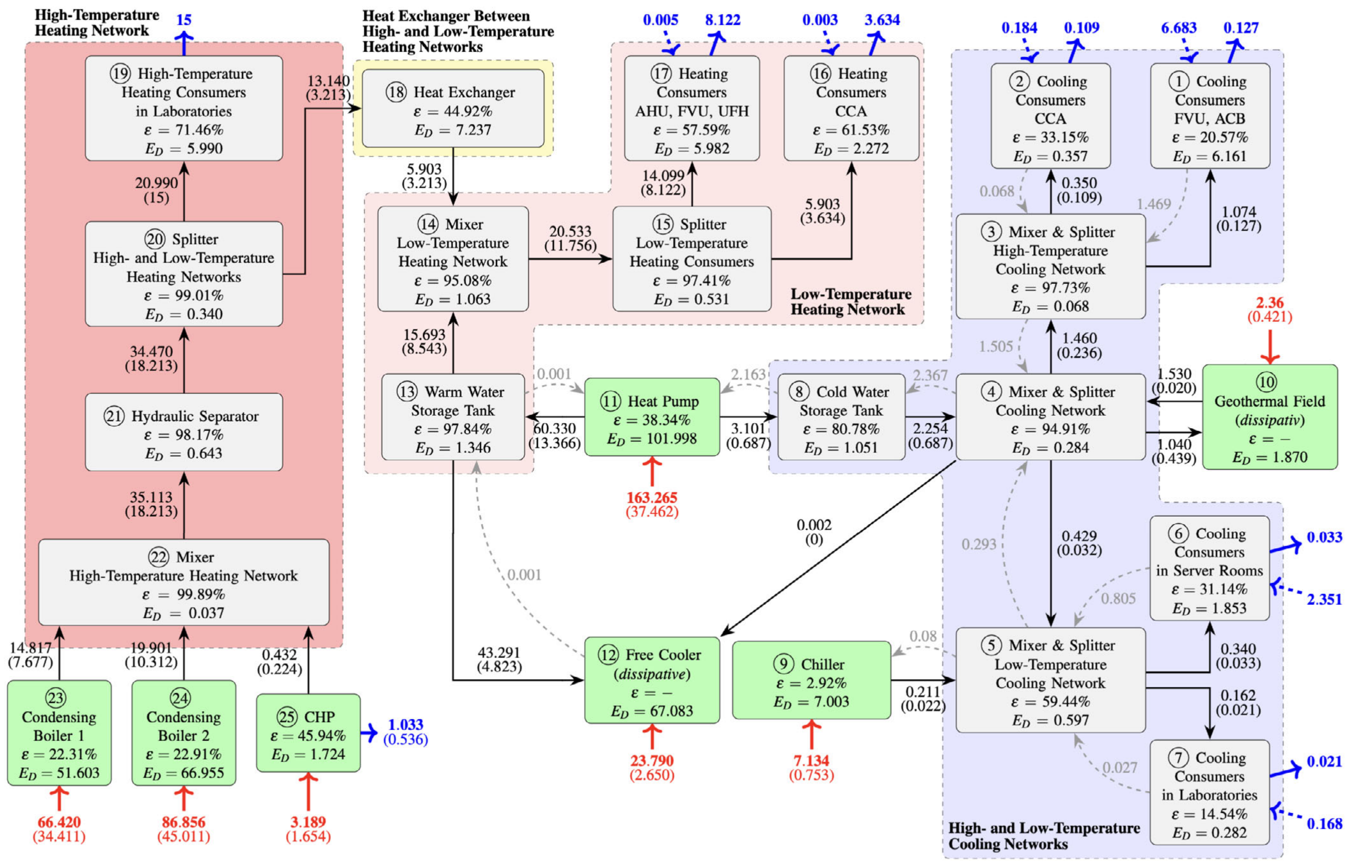

FIGURE 3 The block diagram used in the method of serial arrangement for the application of a dynamic advanced exergy analysis to the energy system of the E.ON ERC building based on the operation of the system in the entire year 2015. All exergy flows between components as well as exergy destructions within the components are integrated over the year 2015 and are in MWh [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Final exergetic products of the heating and cooling system of the main building of the E.ON ERC integrated over the year 2015 (all units are in MWh)

		Exergetic demand		
	Sub-system	**Positive**	**Negative**	**Final exergetic product**
1	Cooling consumer FVU and ACB	0.127	6.683	0.127
2	Cooling consumer CCA	0.109	0.184	0.109
6	Cooling consumer in server rooms	0.033	2.351	0.033
7	Cooling consumer in laboratories	0.021	0.168	0.021
16	Heating consumer CCA	3.634	0.003	3.634
17	Heating consumer AHU, FVU and UFH	8.122	0.005	8.122
19	Heating consumer in laboratories	15.000	0	15.000
25	Gas-fired combined heat and power unit	1.033	0	1.033

process and must be wasted/destroyed elsewhere in the system to cover the cooling requirements of this zone again. The effect of the reference temperature on the supplied and gained exergies in a cooling consumer is depicted in Figure 4.

In Figure 3, the dashed lines between different sub-systems represent the increase in the supplied exergy to different sub-systems. These lines, as well as the negative exergy demands entering the heating and cooling consumers, show the effect of the fluctuations in the

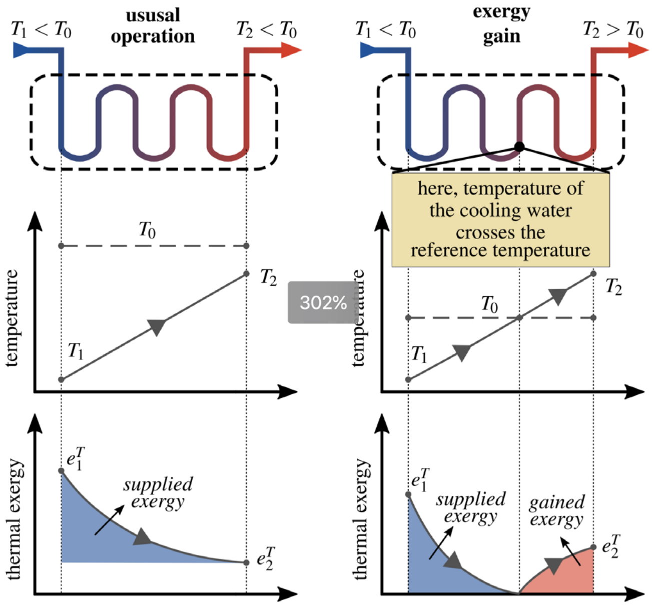

FIGURE 4 Increase of the exergy supplied to a cooling consumer due to a change in the reference temperature [Colour figure can be viewed at wileyonlinelibrary.com]

reference temperature on the results of an advanced exergy analysis. The unfavorable "exergy gains" within cooling processes are caused solely by the changes in the reference temperature, and therefore, they are only calculated and shown but not included in the idealization of the system and in the calculation of endogenous and exogenous exergy destructions. This assumption also simplifies the problem to some extent.

3.5 | Endogenous exergy destruction

Calculation of the endogenous exergy destruction within component k is based on the assumption that all components of the system, except component k, operate ideally without any exergy destructions or losses. In this way, all external sources of inefficiencies in component k are removed, and the only cause of the exergy destruction would be the intrinsic thermodynamic inefficiencies in the same component. This part of exergy destruction is called endogenous exergy destruction and is smaller than the total exergy destruction within the same component when the entire system is in the real operation.

It must be noted that the idealization of the rest of the components must not change their arrangement and the structure of the process flow diagram, and as mentioned before, the final product of the system must be kept the same as in the real operation mode.

To explain the procedure of calculating endogenous exergy destruction, the sub-system 18, "heat exchanger," is considered as an example. In the idealization process, since we must assume that every component, except the heat exchanger, has an exergetic efficiency of 100%, the product exergy of this heat exchanger would be lower than in the real operation. This parameter is shown in parentheses in Figure 3 and is equal to 3.213 MWh. We also assume that the heat exchanger operates with its real exergetic efficiency given in Table 1 and in the heat exchanger block in Figure 3 which is equal to 44.92%. Finally, the endogenous exergy destruction in this component can be calculated as shown in Equation (5):

$$E_{\mathrm{D},18}^{\mathrm{EN}} = E_{\mathrm{P},18}^{\mathrm{ideal}} \cdot \left(\frac{1}{\varepsilon_{18}} - 1\right) = 3.213 \times \left(\frac{1}{0.4492} - 1\right) = 3.940\,\mathrm{MWh}. \tag{5}$$

3.6 | Exogenous exergy destruction

Once the endogenous exergy destruction in each component of the system is known, the exogenous part can directly be obtained by subtracting the endogenous exergy destruction from the total exergy destruction:

$$E_{\mathrm{D},k}^{\mathrm{EX}} = E_{\mathrm{D},k} - E_{\mathrm{D},k}^{\mathrm{EN}}. \tag{6}$$

In order to deepen our understanding of the interactions between system components, the exogenous exergy destruction can be split further into smaller parts, each one of them represents the portion of inefficiencies in component k caused by another component of the system, j. These binary interactions between each pair of the system components are obtained based on virtual scenarios, according to which, only two components of the system are in the real operation (components k and j), while the remaining components operate ideally with an exergetic efficiency of 100%. In this case, the exergy destruction within the kth component is usually higher than the endogenous one calculated before but lower than the total exergy destruction within this component. This new exergy destruction is denoted by $E_{\mathrm{D},k}\big|_{k,j:\mathrm{real}}^{\mathrm{others:ideal}}$. Exogenous exergy destruction within the component k caused by the irreversibilities in the component j, can be then calculated by subtracting the endogenous exergy destruction in component k from $E_{\mathrm{D},k}\big|_{k,j:\mathrm{real}}^{\mathrm{others:ideal}}$:

$$E_{\mathrm{D},j\to k}^{\mathrm{EX}} = E_{\mathrm{D},k}\Big|_{k,j:\mathrm{real}}^{\mathrm{others:ideal}} - E_{\mathrm{D},k}^{\mathrm{EN}}. \tag{7}$$

As an example, the binary interdependency between the sub-system 18, "heat exchanger," and the sub-system 16, "heating consumer CCA" is explained here.

First, we assume that only these two sub-systems are in real operation, whereas the rest of the system is ideal. This means that according to Figure 3, the supplied exergy to the sub-system 16 must be the larger one shown outside parentheses (5.903 MWh), but the supplied exergy to the sub-system 17, "heating consumer AHU (air handling unit), FVU, UFH", is the smaller one given inside the parentheses (8.122 MWh) because of the ideal operation of this component. Sub-systems 14 and 15 are ideal, too. Thus, the supplied exergy to these components must be equal to the outgoing exergies from them (5.903 + 8.122 = 14.025 MWh). According to the real operation of the plant, 27.33% of the supplied exergy to the sub-system 14 is provided by the heat exchanger. Assuming that the same share would be covered by the heat exchanger when only sub-systems 16 and 18 are in the real operation, the exergetic product of the sub-system 18 would be 0.2733 × 14.025 = 3.833 MWh. The exogenous exergy destruction in sub-system 18 due to the irreversibilities in sub-system 16 can be then calculated according to the following equations:

$$E_{\mathrm{D},18}\Big|_{18,16:\mathrm{real}}^{\mathrm{others:ideal}} = 3.833 \times \left(\frac{1}{0.4492} - 1\right) = 4.700\,\mathrm{MWh}, \quad (8)$$

$$E_{\mathrm{D},16\to18}^{\mathrm{EX}} = E_{\mathrm{D},18}\Big|_{18,16:\mathrm{real}}^{\mathrm{others:ideal}} - E_{\mathrm{D},18}^{\mathrm{EN}} = 4.700 - 3.940 = 0.760\,\mathrm{MWh}. \quad (9)$$

By following the same procedure, all binary interdependencies between system components can be calculated.

3.7 | Mexogenous exergy destruction

The assumption associated with the calculation of binary exogenous exergy destructions was that only two components of the system operate under real conditions, and the remaining components are ideal. This assumption does not include the simultaneous interactions between groups of more than just two components. The exergy destruction caused by such a kind of interactions is referred to as mexogenous exergy destruction,[21] and is obtained from Equation (10), once all binary exogenous exergy destructions are known. The mexogenous exergy destruction for some components of the system could be negative, which means that the binary interactions of this component with other components result in a higher exergy destruction that the simultaneous interaction with the combination of all system components:

$$E_{\mathrm{D},k}^{\mathrm{MEX}} = E_{\mathrm{D},k}^{\mathrm{EX}} - \sum_{\substack{j=1 \\ j\neq k}}^{n} E_{\mathrm{D},j\to k}^{\mathrm{EX}}. \quad (10)$$

In Equation (10), n denotes the total number of components.

4 | RESULTS AND DISCUSSION

4.1 | Endogenous and exogenous exergy destructions

The percentage of endogenous and exogenous exergy destructions in different components of the heating and cooling system of the E.ON ERC building are shown in Figure 5. As seen in this diagram, the closer the components are to the final products of the system (i.e., heating and cooling demands requested by the building occupants), the expected smaller the share of exogenous exergy destruction would be. The reason is that due to the irreversibilities in the downstream components such as heating and cooling consumers, upstream components need to send more exergy to the downstream components to counterbalance their inefficiencies. This results in higher exergy destructions in the upstream components and increases the portion of the exogenous exergy destruction within them. For the same reason, the exergy destructions within the heating and cooling consumers are entirely endogenous, as these components are at the end of the energy supply chain and are directly connected to the final product of the system. Since there is no other component after these components, they do not need to supply more exergy to compensate other components' irreversibilities, and therefore, their exergy destruction is totally endogenous.

The geothermal field and the free cooler are components that release the thermal energy collected from different zones of the building to the environment. These components, in fact, have no productive purposes when they are studied on a standalone basis. However, the existence of these components is essential for the proper operation of the entire system to fulfill the demand requested by the end-users. Such components are called "dissipative" components. One of the shortcomings of the method of serial arrangement is that it cannot deal with dissipative components. The reason is that these components do not have exergetic efficiencies, and therefore, endogenous and exogenous exergy destructions cannot be obtained by following the procedures explained before. In the present study, this problem is addressed by assuming that all exergy destructions within dissipative

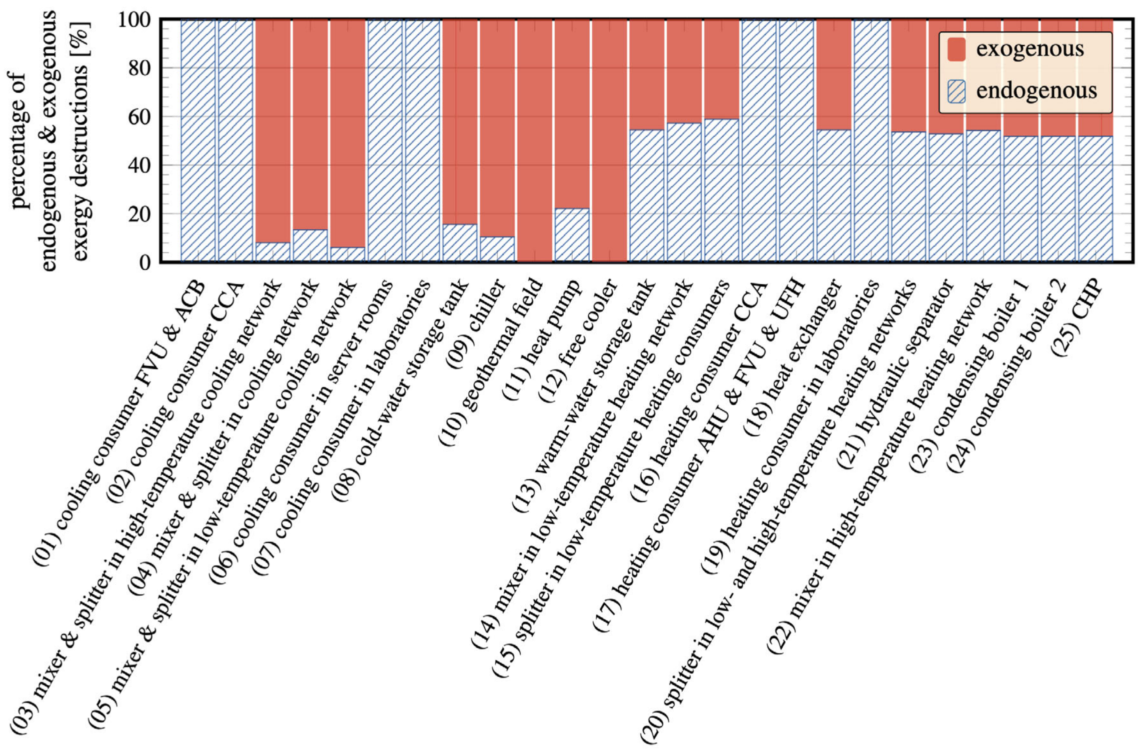

FIGURE 5 The percentages of endogenous and exogenous exergy destructions in different sub-systems of the E.ON ERC building in the year 2015 [Colour figure can be viewed at wileyonlinelibrary.com]

components are exogenous, because if there were no need in other *productive* components of the system, these two components would never be in operation.

Table 3 shows the endogenous, exogenous and mexogenous exergy destructions for all components of the system. This table complements the results illustrated in Figure 5 by providing the same results in numbers.

4.2 | Binary exogenous exergy destructions

Figure 6 presents some of the main results of this study representing the interactions between different components of the system on a binary basis. This figure shows the ratio of exogenous exergy destruction caused by the component j in the component k to total exergy destruction in the component k ($E^{\mathrm{EX}}_{\mathrm{D},j\rightarrow k}/E_{\mathrm{D},k}$). On the x-axis of this diagram, the sub-systems are being sorted based on their total exergy destructions in descending order from left to right.

As expected, heating and cooling consumers are the sub-systems causing a noticeable amount of inefficiencies in the upstream components, not only because they are at the end of the energy supply chain and are attached to the final products, but also because their exergy destructions are relatively large. For instance, the cooling consumers FVU and ACB impose a significant amount of exergy destruction on some other components of the system, such as the heat pump, the free cooler, and the cold-water storage tank.

Another result that can be seen in Figure 6 is that the exogenous exergy destruction in some components of the cooling network, such as sub-system 4, is caused by low-temperature heating consumers (sub-systems 16 and 17). The conclusion that can be drawn is that the interactions between components of the considered system are so strong, that even components of the heating system can cause inefficiencies in the components of the cooling networks. This means that an improvement in a single component of the system might result in a significant increase in the efficiency of the entire system, only if the candidate for improvement is chosen appropriately. This emphasizes the importance of the advanced exergy analysis that can help us to develop optimization solutions and to identify proper candidates for improving the system.

4.3 | The matrix of interactions between different layers of the building energy system

Figure 7 visualizes the endogenous and exogenous exergy destructions in the form of a matrix representing the

TABLE 3 Results of splitting the dynamic exergy destruction in all components of the main building of the E.ON ERC integrated over the year 2015

	Sub-system, k	$E_{D,k}$ (MWh)	$E_{D,k}^{EN}$ (MWh)	$E_{D,k}^{EX}$ (MWh)	$E_{D,k}^{MEX}$ (MWh)
1	Cooling consumer FVU and ACB	6.161	6.161	0	0
2	Cooling consumer CCA	0.357	0.357	0	0
3	Mixer and splitter in high-temperature cooling network	0.068	0.005	0.063	0.035
4	Mixer and splitter in cooling network	0.284	0.038	0.246	0.146
5	Mixer and splitter in low-temperature cooling network	0.597	0.037	0.560	0.261
6	Cooling consumer in server rooms	1.853	1.853	0	0
7	Cooling consumer in laboratories	0.282	0.282	0	0
8	Cold-water storage tank	1.051	0.163	0.888	0.470
9	Chiller	7.003	0.733	6.270	0.762
10	Geothermal field	1.870	0	1.870	1.143
11	Heat pump	101.998	22.602	79.396	13.946
12	Free cooler	67.082	0	67.082	18.563
13	Warm-water storage tank	1.346	0.733	0.613	0.042
14	Mixer in low-temperature heating network	1.063	0.608	0.455	0.012
15	Splitter in low-temperature heating consumers	0.531	0.313	0.218	−0.001
16	Heating consumer CCA	2.272	2.272	0	0
17	Heating consumer AHU, FVU and UFH	5.982	5.982	0	0
18	Heat exchanger	7.237	3.940	3.297	0.225
19	Heating consumer in laboratories	5.990	5.990	0	0
20	Splitter in low- and high-temperature heating networks	0.340	0.182	0.158	0.034
21	Hydraulic separator	0.643	0.340	0.303	0.068
22	Mixer in high-temperature heating network	0.037	0.020	0.017	0.003
23	Condensing boiler 1	51.603	26.733	24.870	5.823
24	Condensing boiler 2	66.955	34.699	32.256	7.532
25	Gas-fired combined heat and power unit	1.724	0.894	0.830	0.642

interactions between different layers of the BES. Each one of these layers includes a variety of components and sub-systems as listed in the table next to this matrix. The reason that the right side of the matrix is empty is because of the assumption used in the method of serial arrangement: exergetic product of an upstream component is the fuel exergy for its adjacent downstream component. Therefore, one limitation of the presented approach is that only downstream components of a system can cause exogenous exergy destructions in the upstream ones, not the opposite way. The diagonal elements of the matrix of interactions correspond to the endogenous exergy destructions.

According to this matrix, the energy supply layer is responsible for 158.809 MWh exergy destruction in the entire system (sum of the values in the first column), among which only 22.897 MWh is endogenous. This means that improving components of this layer (e.g., heating and cooling consumers) would result in a significant improvement of the entire energy system.

Components of the layer energy released to the environment are geothermal field and free cooler, which are both dissipative components and according to the assumption explained before, all exergy destruction in this layer is considered exogenous.

4.4 | The entire system

Results of this study show that a significant part of the total exergy destruction within the main building of the E.ON ERC is exogenous due to the structural limitations of the system and to the strong interdependencies among components. The endogenous exergy destruction can be reduced by applying the best technological measures available in the market. Reducing the endogenous exergy

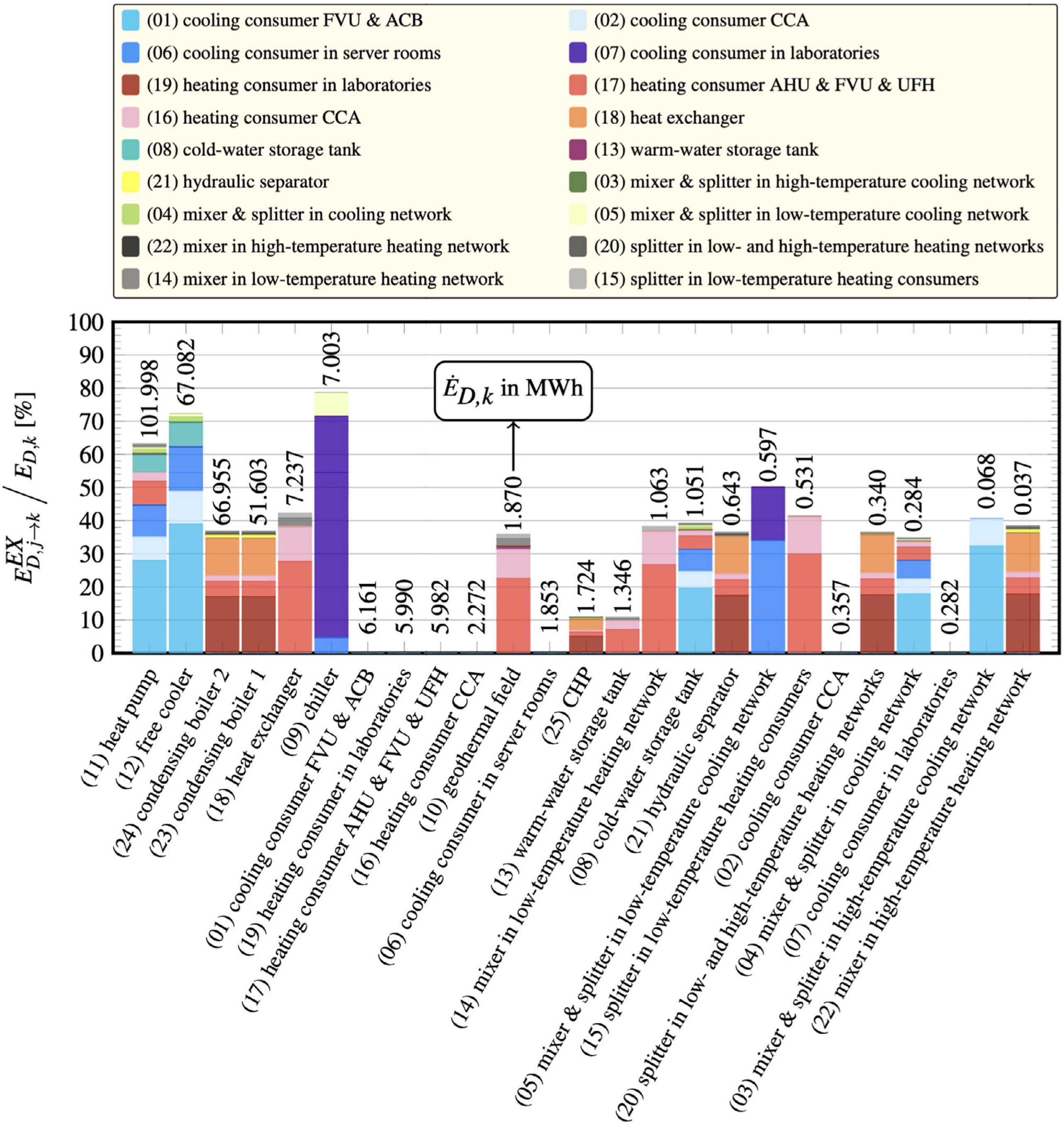

FIGURE 6 The ratio of exogenous exergy destruction caused by component j within component k to the total exergy destruction within component k [Colour figure can be viewed at wileyonlinelibrary.com]

destruction will result is a reduction in the exogenous part too because the exogenous exergy destruction occurs within a component due to endogenous exergy destructions in other components of the system. Nevertheless, this solution is expensive because for decreasing the endogenous exergy destruction, components must be replaced with more efficient ones that usually have higher investment costs. A less expensive way to improve the efficiency of the entire system would be to reduce the exogenous exergy destructions by improving the interactions among the system components through the implementation of a better control system.

4.5 | Potential for improvement

One of the main objectives of analyzing energy systems is to find improvement potentials in a system. Table 4 compares different improvement suggestions for the energy system of the E.ON ERC building obtained from an

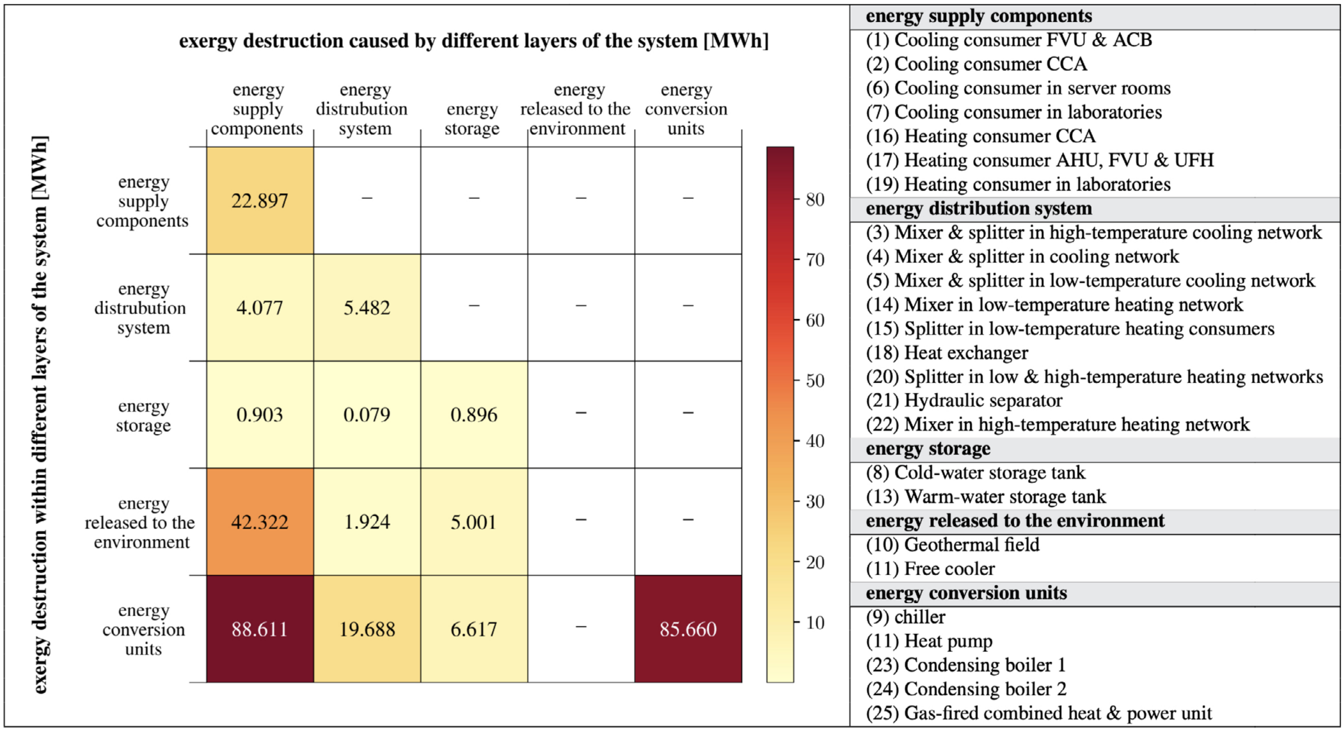

FIGURE 7 Matrix of interactions between different layers of the heating and cooling systems in the main building of the E.ON ERC based on the operation of the system in the year 2015 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Different improvement priorities of the system according to an energy analysis, a conventional exergy analysis, and an advanced exergy analysis (all units are in MWh)

	Energy analysis		Conventional exergy analysis		Advanced exergy analysis	
Priority	Component	Energy loss	Component	Exergy destruction	Component	Importance factor
1	Free cooler	230.12	Heat pump	102.00	Cooling consumer FVU, ACB	61.07
2	Geothermal field	40.56	Free cooler	67.08	Boiler 2	34.70
3	Chiller	28.02	Boiler 2	66.96	Boiler 1	26.73
4	Boiler 2	1.56	Boiler 1	51.60	Heating consumer in laboratories	26.46
5	Boiler 1	1.17	Heat exchanger	7.24	Heat pump	22.60
6	CHP	0.28	Chiller	7.00	Heating consumer FVU, AHU, UFH	22.24

energy analysis as well as from a conventional and an advanced exergy analysis. In this table, the first six components of the system are listed based on their priority to be improved obtained from each analysis.

In an energy analysis, the only criterion that can be used to evaluate the performance of different components is the so-called "energy loss." Therefore, since the free cooler and the geothermal field release a large amount of thermal energy to the environment, they have the highest shares of energy loss and are the first and second priorities for improvement, respectively. However, as explained before, these two components are dissipative components and they only serve other productive components of the system. It would be more rational to find the real causes of energy loss in these two components, but an energy analysis is not able to provide this information.

A conventional exergy analysis refers to the total exergy destruction within system components and suggests the components with highest exergy destruction for improvements. In comparison with energy loss, exergy destruction is a more rational criterion to compare different components because it shows the real thermodynamic inefficiencies within them. However, since the results of a conventional exergy analysis do not distinguish between the internal and the external sources of inefficiencies and only show the total exergy destruction, the improvement priorities obtained from this analysis are not necessarily correct. It depends on the level of interdependencies among components.

In the advanced exergy analysis, a new parameter called "importance factor" is defined, which is a more practical measure to obtain priorities for improvement. For each component of the system, this parameter is equal to the sum of the endogenous exergy destruction within the same component and all exogenous exergy destructions caused by this component in the rest of the system as seen in Equation (11):

$$F_k = E_{\mathrm{D},k}^{\mathrm{EN}} + \sum_{\substack{j=1 \\ j \neq k}}^{n} E_{\mathrm{D},k\to j}^{\mathrm{EX}}. \tag{11}$$

This parameter is a realistic measure that includes both internal and external causes of inefficiencies in a system and can provide more useful suggestions for optimization. As seen in Table 4, according to the results of an advanced exergy analysis, three out of six improvement suggestions are heating or cooling consumers, which cause a large exogenous exergy destruction in other components of the system. An energy analysis and a conventional exergy analysis are not able to identify the important role of these components in the improvement of the entire system.

5 | CONCLUSION

This study proposes a novel approach for calculating endogenous and exogenous exergy destructions within a system in dynamic operations. Our case study is a large, complex and multifunctional building equipped with an extensive monitoring system that provides all input data for the application of advanced exergy analysis to a real-life system. Results of this study are based on the operation of the BES in the year 2015 and indicate that inefficient operations of the downstream components such as heating and cooling consumers cause noticeable thermodynamic inefficiencies in the upstream components such as the boilers and the heat pump. This analysis enhances a conventional exergy analysis by providing useful information about the interactions among different components of a system. For instance, according to the results of a conventional exergy analysis the exergy destruction within components of the energy supply layer is only around 6.8% of the total exergy destruction in the system. Nevertheless, an advanced exergy analysis reveals that the exogenous exergy destruction caused by these components in the rest of the system accounts for more than 41% of the total exergy destruction in the system.

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NOMENCLATURE

c_p	specific heat capacity at constant pressure (kJ/kg K)
e	specific exergy (kJ/kg)
E	exergy (kJ)
$\dot{E}$	exergy rate (kW)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (kPa)
$\dot{Q}$	heat rate (kW)
R	specific gas constant of air = 287.058 (J/kg K)
t	time (s)
T	temperature (K)
$\dot{W}$	power (kW)

GREEK LETTERS

ε	exergetic efficiency (%)
ρ	density (kg/m^3)

SUBSCRIPTS

0	reference state (for exergy analysis)
a	air
C	cooling
D	(exergy) destruction
F	fuel (exergy)
H	heating
i	subscript for streams of matter
in	inlet (stream)
j	subscript for streams of matter and for system components
k	subscript for system components
m	subscript for streams of heat
n	subscript for streams of work
out	outlet (stream)
P	product (exergy)

w water
z zone

SUPERSCRIPTS

EN endogenous (exergy destruction)
EX exogenous (exergy destruction)
MEX mexogenous (exergy destruction)
M mechanical (exergy)
PH physical (exergy)
T thermal (exergy)

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